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Estimating heterotrophic and autotrophic soil respiration in a semi-natural forest of Lombardy, Italy

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ABSTRACT

We studied a semi-natural forest in Northern Italy that was set aside more than 50 years ago, in order to better understand the soil carbon cycle and in particular the partitioning of soil respiration between autotrophic and heterotrophic respiration. Here we report on soil organic carbon, root density, and estimates of annual fluxes of soil CO_2 as measured with a mobile chamber system at 16 permanent collars about monthly during the course of a year. We partitioned between autotrophic and heterotrophic respiration by the indirect regression method, which enabled us to obtain the seasonal pattern of single components.

The soil pool of organic carbon, with 15.8 (±4.5) kg m^{-2}, was very high over the entire depth of 45 cm. The annual respiration rates ranged from 0.6 to 6.9 μmol CO_2 m^{-2} s^{-1} with an average value of 3.4 (±2.3) μmol CO_2 m^{-2} s^{-1}, and a cumulative flux of 1.1 kg C m^{-2} yr^{-1}. The heterotrophic component accounted for 66% of annual CO_2 efflux. Soil temperature largely controlled the heterotrophic respiration (R^2 = 0.93), while the autotrophic component followed irradiation, pointing to the role of photosynthesis in modulating the annual course of soil respiration.

Most studies on soil respiration partitioning indicate autotrophic root respiration as a first control of the spatial variability of the overall respiration, which originates mainly from the uppermost soil layers. Instead, in our forest the spatial variability of soil respiration was mainly linked to soil carbon, and deeper layers seemed to provide a significant contribution to soil respiration, a feature that may be typical for an undisturbed, naturally maturing ecosystem with well developed pedobiological processes and high carbon stocks.

Introduction

Soil is the major organic carbon pool in terrestrial ecosystems (Schlesinger and Andrews 2000); it contains greater amounts of organic carbon (1500 Pg C) than both terrestrial vegetation (550 Pg C) and the atmosphere (780 Pg C) (Houghton 2003). Soils also contribute to the carbon cycle by acting as sources. Soil respiration (R_s) is estimated to be within the range of 64–72 Gt C yr^{-1}, accounting for 20–40% of the annual input of CO_2-C from terrestrial and marine sources to the atmosphere (Houghton and Woodwell 1989; Raich and Schlesinger 1992). In particular, forests have been estimated to contain up to 80% of all aboveground C and about 40% of all underground C (Dixon et al. 1994), so that small changes in C pools of forest soils can significantly affect the global C cycle.

Several biotic and abiotic factors influence soil CO_2 production: soil temperature and moisture (e.g. Epron et al. 1999; Rodeghiero and Cescatti 2005; Chen et al.2011), soil organic matter quantity and quality (e.g. Coûteau et al. 1995), root and microbial biomass, root nitrogen content (Ryan et al. 1996), soil chemical and physical properties, and site productivity (e.g. Subke et al. 2011). Changes in pedoclimate as well as in plant phenological stage may significantly affect variations in R_s throughout the year; it is therefore essential to monitor the seasonal variability of total soil CO_2 flux.

A total 6 different processes were identified in a meta-analytical review of Subke et al. (2006) to contribute to overall CO_2 efflux from soils which are usually grouped into autotrophic and heterotrophic respiration (R_a and R_h). Most difficult to assess are processes with both autotrophic and heterotrophic components (e.g. the rhizomicrobial respiration, heterotrophic decomposition of root exudates and the priming of soil organic matter decomposition by substrate input from live roots). Recent studies have shown that the rhizospheric component may provide a substantial input to the overall soil respiration (Heinemeyer et al. 2007;

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Subke et al. 2011; Heinemeyer et al. 2012). It is well established that autotrophic respiration from roots and root-associated organisms (R_a) significantly contributes to net CO_2 fluxes from soils (Raich and Schlesinger 1992; Epron et al. 1999; Högberg et al. 2001). However, estimates of such contribution are highly variable and consistent and reproducible quantification remain hard to obtain.

According to a review of the main methods of soil respiration partitioning (Hanson et al. 2000), the autotrophic contribution to the total soil CO_2 efflux ranges between 10 and 90%, depending on vegetation type and season of the year. The average contribution for annual studies ranged from 45.8 to 60.4% for forest and non-forest vegetation, respectively. The meta-analysis of Subke et al. (2006) revealed annual contributions of autotrophic respiration in temperate forests between 6 and 71% of total respiration. A recent study of Heinemeyer et al. (2011) gave clear indication that the contribution of root respiration is often underestimated or even omitted because soil collar insertion severed surface roots.

The uncertainty in the estimates of R_s is also due to observations from varied, and sometimes limited, soil depths (Hanson et al. 2000). Studies of respiration partitioning are generally focused on the surface layers of soil. They rarely investigate deeper layers of the soil profile, assuming that the CO_2 flux is mainly generated by upper soil layers (Maier and Kress 2000; Rodeghiero and Cescatti 2006).

Among the various methods for the partitioning of R_s (Kuzyakov and Larionova 2005; Subke et al. 2006), a non-invasive approach to separate the total soil CO_2 flux into its two components is represented by the regression analysis technique. The standard method is based on the assumption that R_h is spatially homogeneous and consequently, the spatial variations of CO_2 flux are mainly due to spatial variation of root respiration: heterotrophic respiration is estimated from the *y*-intercept of the linear regression between CO_2 fluxes and root biomass (Kucera and Kirkham 1971; Behera et al. 1990; Xu et al. 2001). To include the situation of forest ecosystems, where the soil organic carbon (SOC) is also highly heterogeneous, Rodeghiero and Cescatti (2006) introduced a multiple regression method, which accounts for spatial variability of both autotrophic and heterotrophic respiration: the total soil CO_2 efflux is expressed as the sum of the autotrophic and heterotrophic components, linearly dependent on root density and soil carbon content, respectively. In the event that variations of R_s depend on the spatial variability of SOC or root density only, the linear dependence of R_s on SOC or its complementary equation (linear dependence on soil root density) is considered, respectively.

The objectives of this study were to: (i) estimate the annual soil respiration in an undisturbed, naturally maturing forest; (ii) partition soil respiration into autotrophic and heterotrophic components by applying the indirect linear regression method; and (iii) investigate the seasonal variation of autotrophic and heterotrophic respiration rates and their dependence on soil temperature, water content, and radiation.

Materials and methods

Study site

The research site is located inside the fenced territory of the European Commission Joint Research Centre (JRC) at Ispra (Varese, Lombardy, Italy), which covers an area of 155 ha at the eastern side of lake Maggiore in a semi-rural morainic hill area between Po valley and Prealps (45°48′05″N; 8°37′10″E, 209 masl). The annual mean temperature is 12.0 °C, with a minimum of 2.3 °C in January and a maximum of 22.1 °C in July (1973–2002 data; D'Alberti and D'Amati 2004). The annual average precipitation is 1580 mm, with two peaks in spring (199 mm in May) and autumn (200 mm in October), but with high precipitation of more than 100 mm per month for all the vegetation period from March to November.

The experimental site encompasses approximately four hectares and is situated in the centre of a 10 ha mixed forest. The area is crossed along the east–west axis by an artificial concrete tunnel, placed about 50 years ago partially above ground, but now covered completely with soil and vegetation (Fig. 1).

According to the World Reference Base (IUSS/ISRIC/FAO 2006) the soils are mainly Umbrisols (Table 1), with gleyic properties in the lower part of the profile (below 60 cm from soil surface). They are strictly associated with movement of the groundwater table, whose level reaches up to 20 cm from the soil surface only in the south-eastern portion of the site. The soil surface texture is mainly sandy-loam and loamy-sand and the bulk density shows low values of less than 1.1 g cm^{-3} for a depth of about 50 cm; below this limit the soil texture becomes mainly sandy. All soils have a low base saturation and show principally very acidic pH values in the range of 3.7–5.4.

The soils in correspondence with the concrete tunnel are Regosols, with lower organic carbon contents and sandy texture.

Land registers reveal the historic land use of this area starting from the year 1722. At that time, the area was a wet heath land, adjacent to a marsh or a bog. Records from 1873 and 1905 document the terrain as a very wet meadow, adjacent to a marsh and to a damp wood. In the early 1960s, the area was registered as a stable damp meadowland, linked to a small farm inside the bounds of the current research centre, which was abandoned in 1957 during the construction of its infrastructure and facilities. The 10 ha area of the current forest was decided to be set aside as a nature reserve and as a non-managed and non accessible area inside the premises of the JRC. Under such conditions the area was kept undisturbed for more than 50 years, during which a natural conversion to deciduous forest occurred.

The forest now is mainly composed by Pedunculate Oak (*Quercus robur*), Black Locust (*Robinia pseudoacacia*), Black Alder (*Alnus glutinosa*), and Pitch Pine (*Pinus rigida*). Oak is dominant except in the south-eastern area, where Alder prevails as a consequence of the higher water table level. Black Locust mostly extends along the artificial tunnel; Pitch Pine, artificially introduced, is mostly present at the northern and north-eastern edge of the study site. The forest also contains other minor tree species including Common Aspen (*Populus tremula*), Silver Birch (*Betula pendula*), Common Hazel (*Corylus avellana*), and Black Cherry (*Prunus serotina*).

Soil carbon dioxide flux

R_s measurements were performed along two transects (each 136 m long), with axes crossing in NW–SE and NE–SW direction at the position of a fluxtower in preparation (Fig. 1). The transects were selected to capture the variability of the site with regard to soil properties and vegetation types, and to represent the footprint area of the flux tower. Along each transect we installed eight respiration measuring points (collars) some days before start of the measurements for a total of 16 sampling points. The collars were placed at regular intervals of 13.6 m, maintaining a minimal distance of 1 m from any tree or stump and avoiding any ground vegetation inside the collar. Three of the hypothetical plots had to be omitted because disturbed by works for the flux tower. Measurements were made at least two days after a rain event in order to avoid disturbances from water surplus conditions.

R_s was measured at 12 dates distributed about monthly throughout 2008, using a portable infrared gas analyzer LI-6400 (Li-Cor Biosciences, Lincoln, NE, USA), connected to a Li-6400-09 soil flux chamber, which is based on the principle of closed dynamic systems. The chamber is cylindrical with a 9.5 cm diameter, 76.1 cm^2 base area, and 991 cm^3 volume.